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Trilinear Higgs boson coupling variations for di-Higgs production with full NLO QCD predictions in `Powheg`

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Abstract. The couplings of the Higgs boson to other particles are increasingly well measured by the ATLAS and CMS experiments. The Higgs boson trilinear self-coupling however is still largely unconstrained, mainly due to the low cross-section for Higgs boson pair production. We present inclusive and differential results for the NLO QCD corrections to Higgs boson pair production with the full top-quark mass dependence, where the Higgs trilinear coupling is varied to non-SM values. The fixed-order calculation is supplemented by parton showering within the `Powheg-BOX-V2` event generator, and both `Pythia8` and `Herwig7` parton-shower algorithms are implemented in a preliminary study of shower effects.

1. Introduction

Impressive experimental constraints have been set on the Higgs boson couplings to vector bosons and heavy fermions [1, 2, 3, 4]. The Higgs potential, in contrast, leaves more room for New Physics. In particular, the Higgs boson trilinear self-coupling λ can be experimentally constrained by exclusion limits on Higgs boson pair production $pp \to hh$ [5, 6], where the best limit on $\kappa_\lambda = \lambda/\lambda_{\rm SM}$ is currently given by ATLAS with $-5.0 < \kappa_\lambda < 12.0$ at 95% confidence level. Higher-order corrections to Higgs pair production were first calculated in the heavy top-quark mass limit (HTL) $m_t \to \infty$, where the top-quark degrees of freedom are integrated out [7, 8, 9, 10]. The NLO QCD corrections with the full top-quark mass dependence were only computed more recently [11, 12, 13]. The latter are based on numerical evaluations of the two-loop contribution to $gg \to hh$. For non-SM values of the Higgs couplings, results were computed at NLO QCD in the full theory for a class of extensions of the SM in Ref. [14].

In the following, an implementation of the full NLO QCD corrections into the `Powheg-BOX-V2` event generator [15, 16, 17] is presented. In this framework, the Higgs trilinear self-coupling can be varied, as well as the top-Higgs Yukawa coupling. Total cross-sections are computed for $\sqrt{s} = 13, 14$ and 27 TeV at the (HE-)LHC. Differential results are shown for $\sqrt{s} = 14$ TeV. The fixed-order calculation is then matched to both `Pythia8` [18] and `Herwig7` [19, 20] parton showers. For a more detailed description, the reader is referred to Ref. [21].

2. Description of the calculation

The calculation is based on the setup presented in Ref. [22] for the case of the SM. The leading-order amplitude has been computed analytically. The real-emission contributions were implemented using an interface [23] between the `Powheg-BOX` and GoSam [24, 25], where the reduction of the one-loop amplitude has been performed with `Ninja` [26], using master integrals from `golem95C` [27, 28], `OneLOop` [29] and `VBFNLO` [30, 31]. The two-loop amplitude for the full virtual contribution was adapted from Refs. [11, 12], which used an extension of the GoSam package to two loops [32]. There, the integral reduction was performed with Reduze2 [33], and the integrals were numerically evaluated with SecDec3 [34]. For a faster convergence, the integration was performed within a Quasi-Monte-Carlo implementation using a rank-1 shifted lattice rule [35, 36]. The integrals were computed with 16 dual NVidia Tesla K20X GPUs. The top-quark and Higgs masses have been set to $m_t = 173$ GeV and $m_h = 125$ GeV. Thus, the integrals depend only on the two Mandelstam invariants $\hat{s}$ and $\hat{t}$.

A grid for the two-loop amplitude was constructed in both variables using 5291 pre-sampled phase-space points. We split the amplitude in two contributions: diagrams containing the trilinear Higgs coupling are called *triangle-like*, and those that do not are called *box-like* (see Fig. 1 for two diagrams at NLO QCD).

Figure 1. Triangle-like (left) and box-like (right) diagrams contribute to the full amplitude. The former contain the Higgs self-coupling, while the latter do not.

At any order in QCD, the squared matrix-element can thus be written as a second-order polynomial in λ:

$$M_\lambda \equiv |\mathcal{M}_\lambda|^2 = \mathcal{M}_B^*\mathcal{M}_B + \lambda\left(\mathcal{M}_B^*\mathcal{M}_T + \mathcal{M}_T^*\mathcal{M}_B\right) + \lambda^2\mathcal{M}_T^*\mathcal{M}_T \ . \tag{1}$$

The two-loop amplitude for an arbitrary value of λ can be reconstructed from the squared matrix-element computed for three different values of λ. In our case, we chose $\kappa_\lambda = \lambda_{\mathrm{BSM}}/\lambda_{\mathrm{SM}} \in \{-1, 0, 1\}$. A new grid is generated at runtime for the user-defined value of λ, where the amplitude for each pre-sampled phase-space point is calculated as:

$$M_\lambda = M_0 \cdot (1-\lambda^2) + \frac{M_1}{2}\cdot(\lambda+\lambda^2) + \frac{M_{-1}}{2}\cdot(-\lambda+\lambda^2) \ . \tag{2}$$

The grid produced for the two-loop amplitude is fed to an interpolation framework, which interfaces the result at *any* phase-space point $M_\lambda(\hat{s},\hat{t})$ to `Powheg`.

3. Total and differential cross-sections for variations of the trilinear coupling

The results given below are produced using the PDF4LHC15_nlo_30_pdfas sets [37, 38, 39, 40] interfaced to `Powheg` via `LHAPDF6` [41], with the corresponding value of α_s. The top-quark mass is renormalised in the on-shell scheme and is set to $m_t = 173$ GeV, as in the virtual amplitude. The mass of the Higgs boson is fixed to $m_h = 125$ GeV, and the top-quark and Higgs widths are set to zero. Jets are clustered using the anti-k_T algorithm [42] as implemented in `FastJet` [43, 44], with a jet distance parameter of $R = 0.4$ and a minimum transverse momentum requirement of $p_T = 20$ GeV. The central renormalisation and factorisation scales are set to $\mu_R = \mu_F = \mu_0 = m_{\mathrm{hh}}/2$. Scale uncertainties are estimated by 3-point variations $\mu_R = \mu_F = c\,\mu_0$, with $c \in \{0.5, 1.0, 2.0\}$.

Total cross-sections for Higgs pair production at the (HE-)LHC are shown in Table 1, for centre-of-mass energies of $\sqrt{s} = 13, 14$ and 27 TeV and different values of the Higgs self-coupling $\kappa_\lambda = \lambda_{\rm BSM}/\lambda_{\rm SM}$. They are accompanied by their relative scale uncertainties, which are of the order $\mathcal{O}(10-20\%)$. Notably, the K-factors at 14 TeV show a sizeable dependence on the trilinear coupling κ_λ. In the HTL at NLO QCD, Ref. [45] suggested a variation of the K-factors with κ_λ of the order $\mathcal{O}(2-3\%)$. In the full theory, the K-factors are found to vary between 1.56 and 2.15 for values of the trilinear coupling in the range $-5 \leq \kappa_\lambda \leq 12$, see Fig. 2.

$\lambda_{\rm BSM}/\lambda_{\rm SM}$	$\sigma_{\rm NLO}$@13TeV [fb]	$\sigma_{\rm NLO}$@14TeV [fb]	$\sigma_{\rm NLO}$@27TeV [fb]	K-factor@14TeV
-1	$116.71^{+16.4\%}_{-14.3\%}$	$136.91^{+16.4\%}_{-13.9\%}$	$504.9^{+14.1\%}_{-11.8\%}$	1.86
0	$62.51^{+15.8\%}_{-13.7\%}$	$73.64^{+15.4\%}_{-13.4\%}$	$275.29^{+13.2\%}_{-11.3\%}$	1.79
1	$27.84^{+11.6\%}_{-12.9\%}$	$32.88^{+13.5\%}_{-12.5\%}$	$127.7^{+11.5\%}_{-10.4\%}$	1.66
2	$12.42^{+13.1\%}_{-12.0\%}$	$14.75^{+12.0\%}_{-11.8\%}$	$59.10^{+10.2\%}_{-9.7\%}$	1.56
2.4	$11.65^{+13.9\%}_{-12.7\%}$	$13.79^{+13.5\%}_{-12.5\%}$	$53.67^{+11.4\%}_{-10.3\%}$	1.65
3	$16.28^{+16.2\%}_{-15.3\%}$	$19.07^{+17.1\%}_{-14.1\%}$	$69.84^{+14.6\%}_{-12.1\%}$	1.90
5	$81.74^{+20.0\%}_{-15.6\%}$	$95.22^{+19.7\%}_{-11.5\%}$	$330.61^{+17.4\%}_{-13.6\%}$	2.14

Table 1. Total cross-sections for Higgs boson pair production at NLO QCD at (HE-)LHC for centre-of-mass energies of $\sqrt{s} = 13, 14$ and 27 TeV. The scale uncertainties are given in percent.

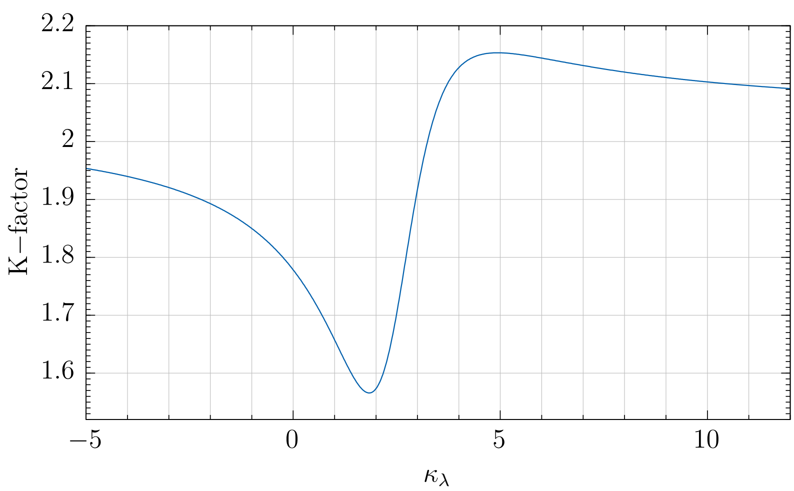

Figure 2. The dependence of the K-factor on the trilinear Higgs self-couplings κ_λ is given at $\sqrt{s} = 14$ TeV in the full theory.

In Fig. 3, distributions of the invariant mass $m_{\rm hh}$ of the Higgs boson pair system are displayed for different values of κ_λ. They exhibit a characteristic dip around $m_{\rm hh} \sim 350$ GeV for values of the trilinear coupling around $\kappa_\lambda = 2.4$. This value of the trilinear self-coupling corresponds to a maximally destructive interference between triangle-like and box-like diagrams. For $\kappa_\lambda = 1$, the maximal destructive interference happens at the hh production threshold and therefore does not manifest itself as a dip, while for κ_λ values larger than ~ 3 the triangle-type contributions start to dominate.

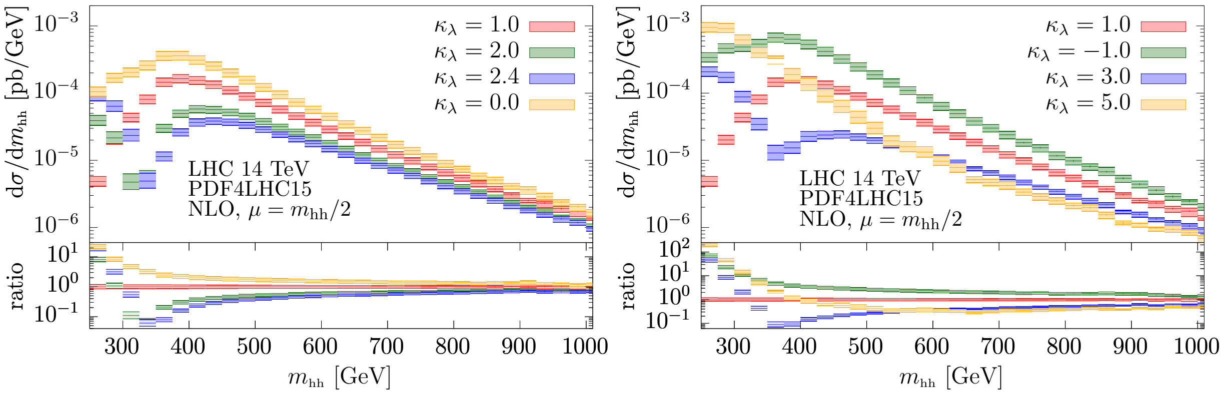

Figure 3. Distributions of the Higgs boson pair invariant mass m_{hh} for various values of κ_λ at $\sqrt{s} = 14\,\text{TeV}$. The uncertainty bands are from scale variations as described in the text.

Note that since the contributions can be separated in triangle- and box-like diagrams, the top-Higgs Yukawa coupling y_t can be simultaneously varied within the same code. A non-SM value of y_t yields in Eq. (1):

$$|\mathcal{M}_\lambda|^2 = y_t^4 \left[\mathcal{M}_B^* \mathcal{M}_B + \frac{\kappa_\lambda}{y_t} \left(\mathcal{M}_B^* \mathcal{M}_T + \mathcal{M}_T^* \mathcal{M}_B \right) + \left(\frac{\kappa_\lambda}{y_t} \right)^2 \mathcal{M}_T^* \mathcal{M}_T \right] . \tag{3}$$

The cross-section can be computed by setting κ_λ in the code to the desired value of the ratio κ_λ / y_t, and rescaling the result by an overall factor y_t^4. For example, $\sigma(y_t = 1.2, \kappa_\lambda = 1) = (1.2)^4\,\sigma(y_t = 1, \kappa_\lambda = 1/1.2)$. Fig. 4 shows the distribution of $m_{\rm hh}$ for values of the top-Higgs Yukawa coupling that are still not experimentally excluded [4].

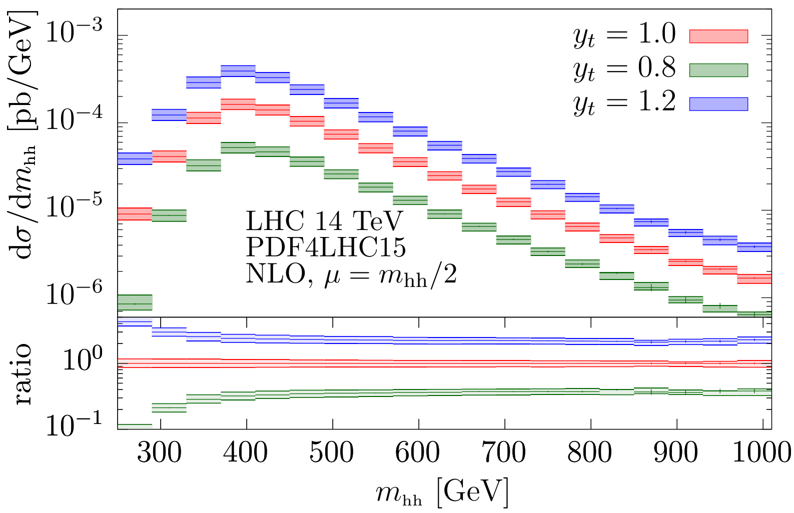

Figure 4. The distribution of the Higgs boson pair invariant mass $m_{\rm hh}$ for values of the top-Higgs Yukawa coupling $y_t \in \{0.8, 1, 1.2\}$.

4. Parton-shower matched results

We now consider NLO distributions matched to a parton shower. The Les Houches Events (LHE) [46] files produced by `Powheg` are used as input to the `Pythia8.235` and `Herwig7.1.4` parton showers. In the case of `Herwig7`, both the default angular-ordered $\tilde{q}$ and the dipole showers are compared. The radiation-regulating `hdamp` parameter in `Powheg` is set to `hdamp` = 250 GeV. Multiple-parton interactions and hadronisation are switched off. The default tunes are used for both parton showers.

Fig. 5 displays the transverse momentum of the Higgs boson pair $p_T^{\rm hh}$ and the separation between the two Higgs bosons $\Delta R^{\rm hh} = \sqrt{(\eta_1 - \eta_2)^2 + (\phi_1 - \phi_2)^2}$. Considering first the distribution of $p_T^{\rm hh}$, both `Herwig7` parton showers (PH7-$\tilde{q}$ and PH7-dipole) generate similar results and reproduce the fixed-order NLO prediction in the far-$p_T^{\rm hh}$ range. In contrast, `Pythia8` agrees with `Herwig7` only for small transverse momenta, while it produces much harder radiation in the tail of the distribution. The same comments apply to the $\Delta R^{\rm hh}$ observable in the region $0 < \Delta R^{\rm hh} < \pi$ where shower contributions are important. Large parton-shower matching uncertainties in Higgs boson pair production have already been discussed in Ref. [47].

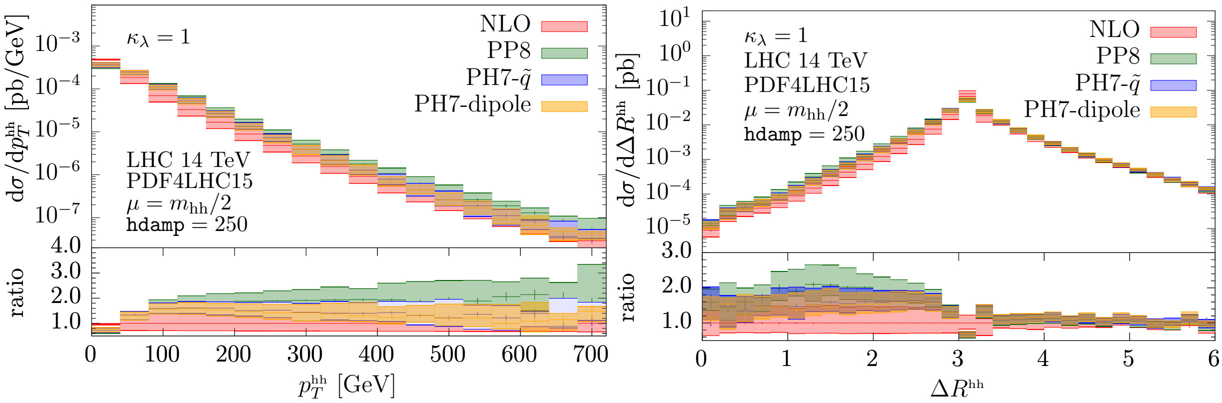

Figure 5. The transverse momentum $p_T^{\rm hh}$ of the Higgs boson pair and the separation between the two Higgs bosons $\Delta R^{\rm hh}$ are shown for the fixed-order NLO calculation and three parton showers, in the $\kappa_\lambda = 1$ case.

5. Conclusion

We have presented a new program package for Higgs boson pair production at NLO QCD with full top-quark mass dependence. In this package, the trilinear Higgs self-coupling can be varied explicitly. Within the same code, simultaneous variations of the top-Higgs Yukawa coupling can also be produced. The public code for the `Powheg-BOX-V2` event generator can be found at the website `http://powhegbox.mib.infn.it` in the `User-Processes-V2/ggHH` subdirectory. In addition, approximations related to the heavy top limit (HTL) can be enabled for comparison purposes. We have found that the full m_t-dependent NLO QCD corrections lead to K-factors which exhibit a sizeable dependence on the value of the trilinear Higgs self-coupling, which is not present in the HTL. We have compared fixed-order predictions at NLO QCD to parton-shower matched results. Both the `Pythia8` and `Herwig7` ($\tilde{q}$ and dipole) parton showers can be matched directly to LHE files produced by `Powheg`. Full particle-level events can be produced with our framework, including Higgs boson decays and hadronisation.

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